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Comparison of Parallel and Serial Methods for Determining Clothing Insulation

ABSTRACT: This paper examines the fundamental differences between the parallel and serial methods for the calculation of clothing insulation using a thermal manikin and demonstrates the differences in the insulation values calculated using these two methods. The parallel method is based on the condition that manikin surface temperatures remain uniform (UST), while the serial method is based on the condition that manikin heat fluxes remain uniform (UHF). Eleven clothing ensembles were evaluated on manikins in UST mode. Three of them were also evaluated on manikins in UHF mode. Insulation values were then calculated using both the serial and parallel methods. Results from UST mode showed that the parallel insulation values ranged from 1.24 to 5.79 clo, while the serial insulation values ranged from 1.43 to 7.98 clo. Differences in the parallel and serial insulations increased as the insulation increased, and the serial insulations were approximately 14–38 % higher than the parallel insulations. Results from UHF mode showed that the parallel insulations were 1.30 clo to 5.89 clo and close to the serial insulations of 1.34 clo to 5.99 clo. In conclusion, the methods of insulation calculation should be determined by the operating mode of the manikin. Only the parallel method should be used when manikins are operated in UST mode and only the serial method should be used when manikins are operated in UHF mode. Insulation values calculated using the incorrect method will be misleading.

KEYWORDS: thermal manikin, insulation, clothing, biophysics, heat transfer

Introduction

Interest in thermal manikins has been growing as sophisticated manikins are used in government, industrial, and academic research settings to evaluate the thermal properties of clothing, cooling garments, footwear, and handwear to determine the protective capabilities and comfort level of clothing in various thermal environments. Several standards, i.e., ISO, ASTM, and EN have been established to standardize test procedures for various applications [1]. The underlying basic principles of manikin operation remain the same, although the construction and control techniques may vary. Manikins are used to determine clothing insulation by measuring the power supplied and the surface temperatures in controlled environments. Most manikins consist of multiple, independently heated and controlled segments. Most manikins have 10–20 segments, but there can be up to 120 segments [2]. The surface temperature and power supplied to each segment are measured and used to calculate the value of clothing insulation for that segment. Total clothing insulation is then calculated from the segmental values. The question is how to accurately calculate the total clothing insulation from the values of the individual segments.

At present, the parallel and serial methods are both used to calculate total clothing insulation from the segmental values. There has been an ongoing discussion over the appropriate use of the parallel or serial methods for calculation of the clothing insulation [1,3–5], as the ISO-15831 and EN-342 standards present both parallel and serial methods for calculation [6,7]. From the perspective of energy balance and heat transfer, the differences between the two methods are apparent. The purpose of this paper is to address the fundamental differences underlying the parallel and serial methods, and illustrate the differences in clothing insulation calculated using both methods.

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Methods

Analysis

The underlying basis for the operation of thermal manikins to measure clothing insulation is the heat balance principle. Insulation is derived from the relationship between heat loss, as represented by power input into the manikin, and the temperature gradient between the manikin surface and chamber temperature. The parallel and serial methods are both derived from the heat balance principle, but are based on methods on how the manikin power inputs are regulated. Thus, the correct method for calculating clothing insulation from segmental insulation values depends on the operating mode of the manikin. In most cases, manikins are operated in the uniform surface temperature (UST) mode. In very few cases, the manikins are operated in the uniform heat flux (UHF) mode. In the UST mode, all segmental temperatures are set to a single constant temperature and power inputs to the individual segments are adjusted to maintain the selected constant surface temperature. By using a uniform temperature, heat transfer among segments is minimized, and the power input to a segment is equal to the heat loss from the segment to the environment. Thus, the insulation of the segment is calculated by:

$$I_i = \frac{(T_i - T_a) \times A_i}{Q_i} \tag{1}$$

where I_i is the insulation of the segment in °C·m^2/W, T_i is the segment temperature in °C, T_a is the chamber air temperature in °C, Q_i is the power input to the segment in W, and A_i is the segmental area in m^2. The insulation can be also expressed in clo units, the conversion factor is 6.45 clo·W/°C·m^2. As the total heat loss is the sum of segmental heat losses, a formula using the insulation of each segment to calculate the total insulation of the clothing is derived as:

$$I_t = \frac{A}{\sum \frac{A_i}{I_i}} \tag{2}$$

where I_t is the total insulation of the clothing in W·°C/m^2 and A is the total surface area in m^2. Equation 2 describes the parallel method for the calculation of total clothing insulation.

In UHF mode, the set-point of the heat flux is constant for all segments and thus heat fluxes over the manikin are equal. Total clothing insulation is calculated by:

$$I_t = \left(\frac{\Sigma(A_i \times T_i)}{A} - T_a \right) \times \frac{A}{Q} \tag{3}$$

As segmental heat fluxes Q_i/A_i are equal to whole body heat flux Q/A, Eq 3 can be rewritten as:

$$I_t = \frac{\Sigma(A_i \times I_i)}{A} \tag{4}$$

Equation 4 describes the serial method for the calculation of clothing insulation.

Measurement process introduces errors. The contribution of a segmental error to the total insulation error differs between the parallel and serial methods. Assume that segment m has an error ΔI_m. Its contribution to the total insulation error can be estimated from Eqs 2 and 4 as follows:

$$\Delta I_t = \left(\frac{I_t}{I_m} \right)^2 \times \frac{A_m}{A} \times \Delta I_m \tag{5}$$

$$\Delta I_t = \frac{A_m}{A} \times \Delta I_m \tag{6}$$

where ΔI_t is the error of total insulation. Our experience with manikins is that measurement errors usually appear in segments where clothing insulations are high. High insulation requires low power supply to the segments; heat fluxes in these segments are very low and result in errors. Consequently it is reasonable to

TABLE 1—*Description of 11 evaluated ensembles.*

No.	Ensemble description
1	Dress uniform, 100 % wool
2	Hot weather dress uniform, 50 % cotton/50 % nylon
3	Work uniform, 100 % Nomex
4	Dress uniform, body armor
5	Dress uniform, cooling vest
6	Dress uniform, T-shirt, body armor, helmet
7	Dress uniform, cooling vest, chem/bio-protective suit
8	Expedition weight underwear and waterproof jacket, pants
9	Dress uniform, T-shirt, chem/bio protective suit, body armor, helmet, mask
10	Expedition weight underwear and down jacket, pants
11	Expedition weight underwear and down jacket, pants

assume that I_t/I_m is near or less than 1.0 for segments where errors likely appear. Under this circumstance, the error of total insulation in Eq 5 would be less than the error of total insulation in Eq 6. In other words, the serial insulation is more sensitive to the segmental error than the parallel insulation.

Measurement

The 11 clothing ensembles listed in Table 1, with evenly or unevenly distributed insulation, were evaluated on two manikins at our Institute to demonstrate differences that occur when the parallel or serial methods are used to calculate the clothing insulation. Manikins were operated in UST mode for all 11 ensembles and in UHF mode for three (i.e., Nos. 3, 8, and 10) of the 11 ensembles. In UST mode, the manikin surface temperature and chamber temperature constants were set to 33°C and 30°C for five ensembles, and 35°C and 20°C (ASTM test conditions) for six ensembles [8]. In UHF mode, the chamber temperature was 20°C, and the set-point of heat flux was equal to the average values of heat flux measured when the manikin was operated in UST mode for the same ensemble. Each ensemble was tested three times to ensure the accuracy of measurements. For comparison purposes, both parallel and serial insulations were calculated, although only the parallel insulation in UST mode or the serial insulation in UHF mode accurately represents the total insulation, as indicated in the derivation process of Eqs 2 and 4.

One of our Institute manikins has 18 independently heated thermal segments plus an additional heated guard segment at the neck mounting plate. The other manikin used for testing has 14 independently heated thermal segments. The segments are wet segments with an integrated sweating dispenser. The manikins are covered with a fabric skin layer to distribute water over the segments surface. Both manikins are controlled by ThermDAC software (Measurement Technology Northwest, Seattle, WA) which regulates operation, records data, and displays real time numerical and graphical plots of temperatures and heat fluxes.

Results

The insulation values for the ten clothing ensembles calculated using the parallel and serial methods using data from a manikin run in the UST mode are shown in the Fig. 1. The parallel insulation values were between 1.24 clo and 5.79 clo, while for the serial method, values were between 1.43 clo and 7.98 clo for ensembles ranging from light clothing to heavy winter clothing. Differences in the parallel insulation and serial insulation increased as the insulation increases. The serial insulations were 14–38 % higher than the parallel insulations. The results of the ensemble 11 are not shown in the Fig. 1, as the calculated serial insulation was an unrealistic high value of 11.41 clo, while its parallel insulation value was only 5.77 clo. Insulation of some ensembles are uniformly distributed, e.g., segmental insulations of ensemble 3 fell within a range of 1.23 clo to 1.59 clo, while insulations of some other ensembles were not uniformly distributed; e.g, segmental insulations of ensemble 10 ranged from 2.78 clo to 8.38 clo.

The parallel insulation and serial insulation values of the three ensembles measured with the manikin operating in UHF mode or UST mode are listed in the Table 2. In UHF mode, the parallel and serial insulation values were close. Those values were also close to the parallel insulations measured with the

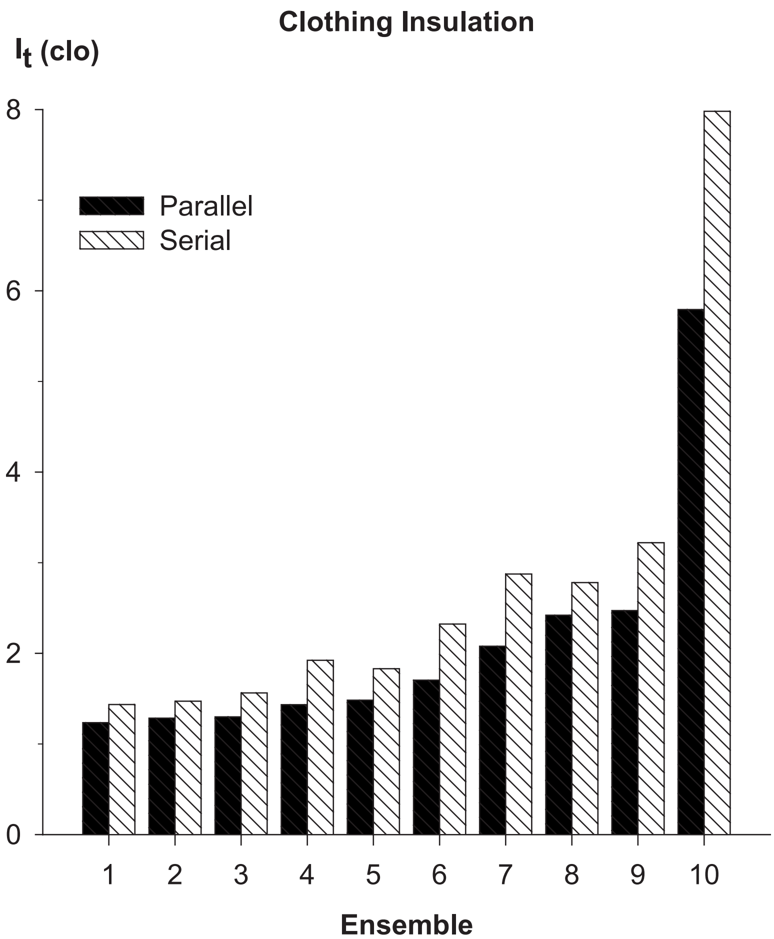

FIG. 1—*Clothing insulation values calculated using the parallel and serial methods for ten ensembles tested with the manikins in the uniform skin temperature mode.*

manikin operating in UST mode. However in UST mode, the insulation values calculated using the serial method were clearly higher than values calculated using the parallel method.

Discussion

The comparison of the parallel and serial methods for the calculation of clothing insulation values, as well as the results calculated using these two methods, clearly demonstrated that the parallel method should be used when the manikins are operated in UST mode and the serial method should be used when the manikins are operated in UHF mode. The use of the parallel method in UST mode and the serial method in UHF mode yield values which accurately represent the total insulation provided by the clothing. The derivation of Eq 2 and 4 clearly indicated that the use of the serial method with data collected in UST mode, or the parallel method for measurements made in UHF mode, will not yield insulation values which

TABLE 2—*The parallel and serial insulation values for ensembles 3, 8, and 10 (see Table 1) with the manikins in the uniform skin temperature mode and the uniform heat flux mode.*

No.	Operating mode	Parallel clo	Serial clo
3	UST	1.27	1.45
	UHF	1.30	1.34
8	UST	2.42	2.78
	UHF	2.36	2.39
10	UST	5.74	7.98
	UHF	5.89	5.99

are truly representative of the actual insulation provided by the clothing. There are ongoing debates and conflicting facts regarding which of the two methods should be used for the calculation of the clothing resistances. Thus, confusion obviously exists and some manikin users believe that it may be appropriate to use both methods at the same time [9]. This paper should helps users to understand the differences in these two methods and to choose the correct calculation method.

When manikins were operated in UST mode, insulation values calculated using the serial method were higher than results calculated using the parallel method. This was consistent with previous observations [5,10]. Unrealistically high insulation values will result in poorly informed clothing selections when clothing is selected on the basis of insulation properties. Inaccurate insulation values will also result in errors when used as input into human thermoregulatory models that predict heat or cold strain. If serial insulations were used for whole body heat balance analysis, the predicted values of heat losses would be underestimated by approximately 13–27 %. When serial insulation values were used to calculate the level of clothing insulation required by workers to sustain their activities during exposure to significant cold stress, results from a physiology study demonstrated that the human subjects were not able to achieve and maintain heat balance while wearing that level of cold protection [4]. The clothing insulation value calculated using the serial method was too high and thus did not reflect the actual insulation, i.e., the actual level of protection from the cold, provided by the clothing.

Another observation was that the serial method for calculating total insulation was sensitive to the insulation values of the individual segments. Hence, an error in just one segment can skew the final total insulation value. For example, the serial insulation of the ensemble 11 was as high as 11.41 clo because of a measurement error from one segment. Although this segment represented only 8.5 % of surface area, the influence of its measured insulation of 51.3 clo was obvious in the serial method. If the error was excluded from the calculation, the serial insulation was reduced to 7.69 clo. When compared to the serial method, the influence of the segmental error on the total insulation error was smaller in the parallel method. The parallel insulation of ensemble 11 was 5.32 clo when the erroneous segmental value was not included, and the parallel insulation was 5.77 clo when the erroneous segmental value was included. This observation was consistent with the error analysis as shown in Eqs 5 and 6, and the contribution of a segmental error to the total insulation error is greater in the serial method than in the parallel method. When one manikin segment was much better insulated relative to the others, its heat loss was very low, causing the measured insulation value of the segment to be too high, and the resulting serial insulation for the total body to be unrealistically high [10]. This becomes more problematic when the number of segments increases. As almost all manikins use computer-based operating systems with software that automatically calculates insulation values, manikin users are usually not involved in data handling or calculation, and only see the displayed output. Consequently, users may not be aware of measurement errors. Thus, results calculated by incorrect methods will be very likely misleading.

When manikins were operated in UHF mode, the parallel insulation values were nearly equal to the serial values, as shown in Table 2. However, in theory only the serial method should be used because the parallel method could not be derived unless segment temperatures over the manikin are all maintained at a constant value. The serial insulation correctly represents the total clothing insulation in UHF mode. In addition, the derivation of Eq 4 from Eq 3 contains a systematic error. When the heat fluxes are held uniform, surface temperatures are often not uniform and temperatures of the individual segments can differ, thus violating an inherent assumption of the serial method. Temperature gradients up to 6°C were observed in our study when manikins were in UHF mode. Those large temperature gradients cause heat exchange from high to low temperature segments. In other words, as some heat is gained or lost to adjacent segments, the power input to the segment does not accurately reflect the heat loss from the segment to the surrounding environment, and thus the segmental insulation cannot be correctly calculated by Eq 1. Therefore, Eq 3, rather than Eq 4, should be used to calculate clothing insulation.

Conclusions

The parallel method was based on the condition of a uniform surface temperature of the manikin, whereas the serial method was based on the condition of a uniform heat flux over the manikin. Thus, a method for the calculation of clothing insulation is dependent on the operating mode of the manikins. Only the parallel method should be used when manikins are operated in UST mode, and only the serial method should be used when manikins are operated in UHF mode. The serial method and the parallel method should not be normally used at the same time. Insulation values calculated using the incorrect method will be misleading.

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